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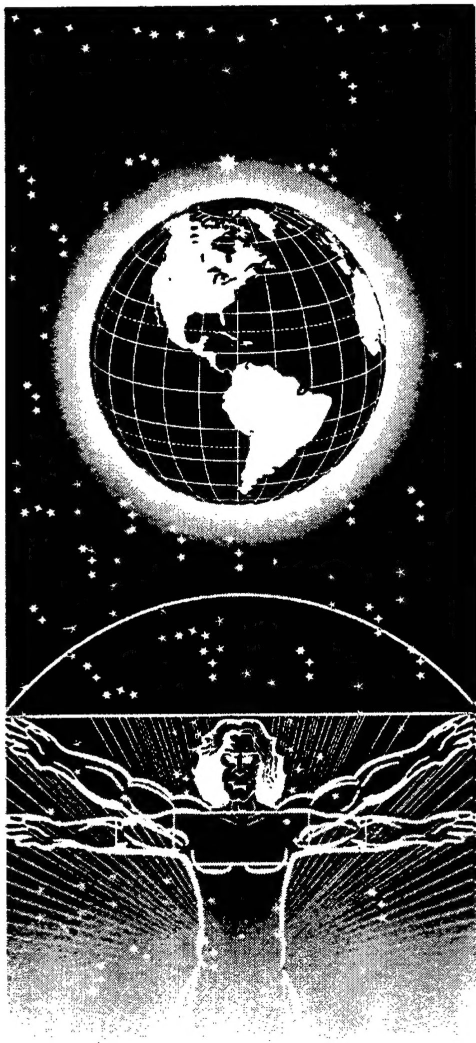

UNITED STATES AIR FORCE RESEARCH LABORATORY

INSTRUMENT SCAN STRATEGIES OF F-117A PILOTS

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
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13. ABSTRACT *(Maximum 200 words)*

Eye tracking is an accurate and objective means of measuring an instrument scan pattern. The purpose of this study was to determine if prior aircraft experience, phase of flight, and autopilot mode modulated the instrument scan pattern of F-117A pilots. Twenty-three F-117A pilots, grouped by prior experience, flew an instrument approach manually and with autopilot while wearing and El Mar eye tracker in the F-117A simulator at Holloman AFB NM. Number if fixations, dwell time, and percent total dwell time spent on nine individual instruments was collected and analyzed. The primary flight instrument was determined on the basis of pilot experience, and usage of the primary flight instrument varied significantly with phase of flight and manual vs. autopilot when ANOVA analysis was performed.

Prior aircraft experience affects development of an instrument scan in a new aircraft. Prolonged dwell times on the primary flight instrument and change in fixations/dwell time during autopilot mode have implications for instrument design as well as cognitive load during novel situations. Further studies should be pursued.

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INSTRUMENT SCAN STRATEGIES OF F-117A PILOTS

Over fifty years have passed since Fitts, Jones, and Milton conducted a series of investigations to gather data on pilots' eye movements during instrument approaches. Their research subsequently formed the basis for the classic "T" arrangement of instruments around the attitude indicator (4). Since then much work has been done in elucidating the process of scanning aircraft instruments.

A pilot's scan is a subconscious, conditioned activity that is situation dependent, utilizing a home base instrument. The instrument scan reflects the information needs of the pilot based upon his mental model for a specific phase of flight. It follows then that a scan can be inadequate if the mental model does not accurately describe the phase of flight, such as may occur with a novice pilot (5). Similarly, the subconscious nature of a scan can be disrupted by a conscious input, an emergency for example, with a resultant stare while processing information. Such a breakdown in the scan is more pronounced in the less experienced aviator, indicating an increased mental workload (8). This is important in the maintenance of situational awareness and spatial orientation.

Eye tracking can be used to study how cockpit design modulates scanning behavior (7) or the reverse, using scanning behavior to provide valuable insight into cockpit design (1). Defining instruments by type based on average dwell time and percent dwell time led to major implications for instrument design (6). Information-rich electronic displays result in longer dwell percentage and average dwell time. Adding an autopilot shortens dwell times and allows an expansion of the crosscheck to other instruments (8).

Eye tracking technology has also been useful in elucidating the effects of training or directing training efforts. For instance, scanning behavior improved as untrained participants increased in skill level, showing that eye scan behavior was directly linked to skill (3). Belenkes' study of novice versus expert pilots added much to the understanding of attention flexibility and mental model development (2). Finally, introduction of eye tracking at a functional level in the training of fighter pilots, using real-time feedback, improved skill acquisition in simulator training (9). In summary, data from eye tracking studies is valuable for describing pilot workload and situation awareness, for inferring information transfer from displays, for guiding display design, and for training pilots.

Because of reports of spatial disorientation in the F-117A Nighthawk, we utilized eye tracking technology to ascertain the instrument scan strategies of F-117A pilots. The "glass cockpit" design of the F-117A, consisting of Color Multifunction Display Indicators (CMDI) and the head-up display (HUD), departs from the classical analog instrument "T configuration (Figure 1). The left CMDI, configured as a vertical situation display (VSD), represents attitude, heading, altitude, and airspeed. The VSD is separated from the horizontal situation indicator (HSI) on the right CMDI by seventeen inches. Since the two CMDIs have such a large angular separation, the pilot is forced to move both head and eyes in order to shift his scan from one CMDI to the other. To complicate matters, alternate analog electromechanical instruments are located on the far-left instrument panel.

It can be seen then that the pilot has a wealth of information presented in both digital and analog format. Because only experienced pilots are selected to fly the F-117A, they are expected to form their own scan pattern; that is, no specific scan strategy is taught in initial conversion training. The purpose of this study was to determine if (1) prior aircraft experience affects the establishment of a primary flight display, (2) if the phase of flight affects the establishment or the use of the primary flight display, and (3) if engaging the autopilot modulates the scan pattern used during manual flight.

METHOD

Participants

The study protocol was approved by the Institutional Review Board, Air Force Research Laboratory, Wright-Patterson AFB OH. Informed consent was obtained from the participants. Twenty-three male F-117A pilots with a mean age of 36 years (range 30-42) from Holloman AFB NM, participated in the study. F-117A experience ranged from student (11 hours) to senior instructor pilot (700 hours), with a mean of 261 hours. It must be noted that pilots selected to fly the F-117A have a minimum of 750 hours of fighter time. Thus the pilot with only 11 hours in the F-117A was not a novice pilot. No females were included in the study because there were no female F-117A pilots.

Equipment

The study was conducted at Holloman AFB NM in the F-117A simulator, a dynamic high fidelity trainer that replicates actual aircraft performance, navigation and weapon systems. Eye scan measures were collected with an El Mar, Inc. (Ontario, Canada) Vision 2000 Portable Eye Measurement System. The eye movement data were collected at 60Hz. These data along with video from the head mounted scene camera were recorded onto videotape. A detailed description of this system may be found elsewhere (10).

Flight Task

Pilots flew the precision approach as shown in Figure 2 three times, once fully coupled to autopilot/autothrottle and twice manually. The second and third trials were identical except an unusual attitude was discreetly inserted during the third trial. The approach was divided into eight segments, or phases of flight (Figure 2). The segments were flown in numerical order and required at least one change to airspeed, altitude, or heading between segments.

The approach was flown in simulated night weather down to approach minimums. The participants were asked to fly the published approach as accurately as possible while maintaining their normal instrument scan, starting with one turn in holding, followed by the penetration down to the missed approach point. Then the simulator was frozen signifying the end of the trial. The time required to complete all eight segments of the approach was about 13 minutes.

Procedure

At the beginning of each session the participant completed a questionnaire about his aircraft experience and signed an informed consent document. The participant then received a standardized briefing on the background of the study and the experimental task. In the simulator cockpit, the eye tracker was adjusted on the participant's head and calibrated. Each participant was allowed a three-minute familiarization flight. The simulator was then initialized to the starting position for the approach. There was a 15-minute break between the three trials to allow flight performance data to be saved and downloaded. When the flight task was completed, the participant was debriefed.

Analysis Framework

Only the autopilot trial and the first manual trial were analyzed. The third manual trial in which an unusual attitude was inserted will not be discussed in this paper. Dependent measures of eye movement were collected in terms of number of fixations, dwell time, and percent total dwell time spent on individual instruments. A fixation was defined as stationary eye movement within a 30-degree radius for 183 ms. Because the duration of the phases of flight differed, number of fixations per minute was reported as a dependent measure. Dwell time was defined as the total time looking at an instrument divided by the number of fixations on that instrument. The percent total dwell time was defined as the total time spent looking at an instrument divided by the total time spent looking at all the instruments. Collectively, these measures defined the pilot scan strategy. Eight segments, or phases of flight, were defined. Because Segments 1 and 3 were level phases of flight, and Segments 2 and 4 were level turns, these were combined, resulting in analysis of six phases of flight. The data was analyzed for each phase of flight and for method of flight control (autopilot or manual).

Each pilot was assigned to one of four groups based on prior aircraft experience: A-10, F-111, F-16/15, or Miscellaneous. Pilots in the Miscellaneous group flew C-29, F-4, B-1 and Royal Air Force Hawk aircraft. No between-group analysis was conducted because previous aircraft experience was considered a confounded factor. The motivation for this study was to determine how pilots of the same background developed scan strategies for the F-117A. Therefore analyses of phase of flight by method of flight control were conducted for each pilot group. Data from two pilots were not analyzed because of missing values due to equipment malfunctions during data collection. Consequently, the analysis reported here represents twenty-one pilots.

RESULTS

Primary Flight Instrument

Initial analysis focused on nine specific cockpit instruments: VSD, HSD, Head-up Display (HUD), Data Entry Panel (DEP), digital engine instruments, and four analog instruments (altimeter, attitude indicator, horizontal situation indicator, and radar altimeter). After means across pilot group and phase of flight were analyzed for the dependent variables, one instrument per group was identified as the primary flight instrument. The VSD was the primary flight

instrument for the A-10, F-111, and Miscellaneous groups, and the HUD for the F-16/15 group (Table I). Hence, only the VSD and HUD will be discussed in the remaining results.

Primary Flight Instrument Usage During Phases Of Flight

Number of fixations per minute on the primary flight instrument varied significantly across the phases of flight for all groups (Figure 3). Analysis showed a signficant main effect of phase of flight for the F-16/15 group ($F(5,15) = 3.45$; $p<0.05$), the A-10 group ($F(5,20) = 3.13$; $p<0.05$), the F-111 group ($F(5,30) = 3.85$; $p<0.05$), and the Misc. group ($F(5,20) = 2.94$; $p<0.05$).

Dwell time only showed significant main effect of phase of flight for the F-111 group ($F(5,30) = 7.69$; $p<0.05$).

Percent of total dwell time revealed significant effects for the VSD. There was significant main effect for the A-10 group ($F(5,20) = 3.25$; $p<0.05$), and the F-111 group ($F(5,30) = 6.04$; $p<0.05$).

Primary Flight Instrument Usage During Autopilot And Manual Flight

Number of fixations per minute on the primary flight display did not vary significantly between autopilot and manual flight across groups. However, there was a significant interaction of primary flight display and phase of flight in the F-16/15 group ($F(5,15) = 4.68$; $p<0.05$) for autopilot. The F-16/15 group alternated between the HUD and VSD as their primary flight instrument during the six phases of flight while flying coupled with autopilot. This group was the only group found to have modified their use of the primary display as a result of flying coupled with autopilot verses manually (Figure 4).

Dwell time revealed a significant main effect of autopilot verses manual flight for the F-111 group ($F(5,30) = 7.69$; $p<0.05$).

Percent of total dwell time spent on the VSD during autopilot and manual flight is shown in Figure 5. There were significant main effects for the A-10 group ($F(1,4) = 122.07$; $p<0.05$), F-111 group ($F(1,6) = 40.99$; $p<0.05$), and Miscellaneous group ($F(1,4) = 117.52$; $p<0.05$).

Fixations And Dwell Time On The Primary Flight Instrument

Each group visited the primary flight instrument more frequently in autopilot mode than during manual flight, but dwelled on the instrument less than half the time in autopilot than manual. For example, the A-10 group recorded 9.77 fixations per minute at a dwell time of 6.88 seconds for manual flight; however, during autopilot flight the number of fixations per minute increased to 15.04 while the dwell time decreased to 2.66 seconds. The average across groups was 13.1 fixations/minute in manual and 15.3 in autopilot, and dwell time was 4.5 seconds in manual and 1.9 seconds in autopilot. During manual flight, pilots viewed the primary display 78% of the time (percent total dwell time) and 48% of the time during autopilot flight. Put another way, 14-28% of the time the pilots were looking at "other" areas during autopilot flight compared to 5-9% of the time in manual flight.

DISCUSSION

Objectively documenting the scan strategies of F-117A pilots during an instrument approach provides empirical knowledge on how pilots adapt their flying experience to a new cockpit. The initial supposition was that pilots with glass cockpit/HUD experience (F-16/15) would tend to rely upon the HUD, whereas pilots used to electromechanical instruments (A-10, and to some extent, F-111) would either reference the standby instruments or some combination of the available instruments. Results showed the F-15/16 group, although small (n=4), clearly preferred the HUD to the VSD, while the remaining groups relied primarily on the VSD. None of the pilots spent a significant amount of time on the alternate electromechanical instruments. Apparently experienced "round dial" pilots adapt easily to electronic, digital display of flight data. A contributing factor could be that the analog alternate instrument cluster is 22.5° left of design eye reference, an unnatural gazing angle for instrument flight.

It can be inferred that, the higher the number of fixations on an instrument, the more important is that instrument in the pilot's crosscheck. In this study the VSD was the most visited instrument for all groups except the F-16/15 group, which used the HUD as the home instrument. The crosscheck radiated around these two primary attitude instruments. Additionally, the number of fixations on the home instrument varied significantly with phase of flight. Intuitively this makes sense. For example, one would expect more fixations during the final approach than during straight and level flight at altitude. The dwell time on the VSD was also quite long, averaging 5.4 seconds per fixation for the A-10, F-111, and Miscellaneous groups. The prolonged time can represent two factors: that information was difficult to extract, requiring greater cognitive effort, or that information was rich, requiring greater time to read the various sources. Because the VSD displays attitude, altitude, heading, and airspeed information, the longer dwell time may be a combination of both. Further study needs to be done to distinguish between the two factors, especially since prolonged cognition can lead to a delayed decision.

During autopilot flight, the pilots visited the primary flight display more frequently than during manual flight but spent less time per fixation. This can be thought of as "minding the store;" that is, the pilot does not have to make a control input, rather he must simply confirm that the current aircraft state matches his expectations. This in turn allows the pilot to spend more time viewing "other" areas. Autopilot control decreases the pilot's workload, especially during target acquisition and weapons release, but it is a two-edged sword. It is possible that, during the time spent in other areas, the pilot is out of the loop and, if a novel situation occurred, the pilot could waste precious seconds reestablishing situational awareness. Since the majority of F-117A operations are conducted coupled in autopilot, it is important to emphasize in initial and continuation training the necessity for maintaining a spatially orienting crosscheck of instruments.

CONCLUSION

Eye tracking technology is an accurate and objective means of providing a window into a pilot's cognitive processes, a very slippery entity to grasp at best. Studying an operational aircrew population in their working environment is a potential gold mine of human factors

understanding that can be applied to the ergonomic design of cockpits and development of training programs. All the pilots in this study preferred a digital primary instrument, with the F-16/15 group preferring the HUD. Therefore, prior experience does affect development of an instrument scan pattern and should be considered during initial training in a new aircraft. Longer dwell times on multifunction displays, coupled with more time looking elsewhere during autopilot flight, bets the question of what would happen during a novel situation. Does the process of perception, comprehension, and integration break down, or is it perhaps enhanced? Does the pilot quit his normal scan and search for other sources of information? These questions bear directly on the constant situation awareness required during the employment of today's complex weapon systems, and they become even more important in the super-agile aircraft of tomorrow. It is incumbent on the aeromedical profession to meet the challenge.

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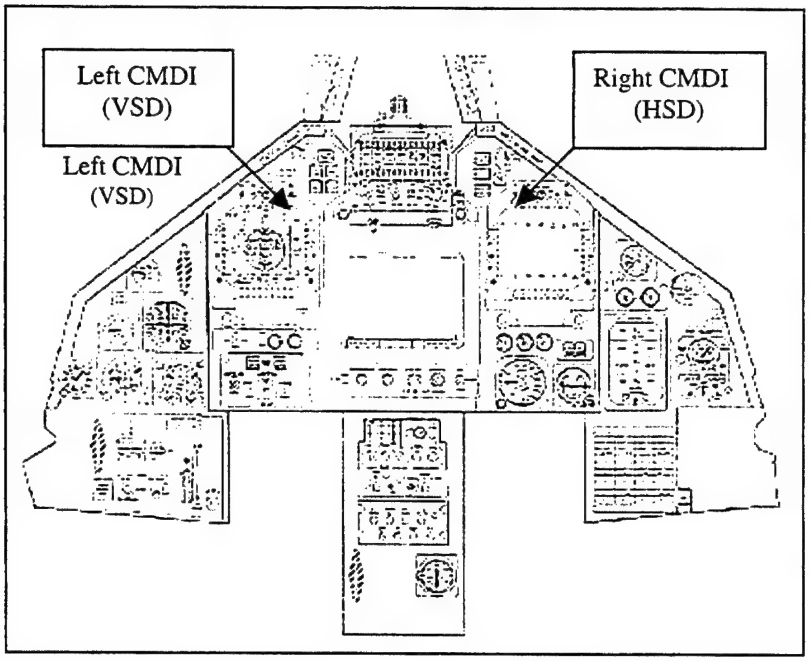


Figure 1. F-117A Instrument Panel

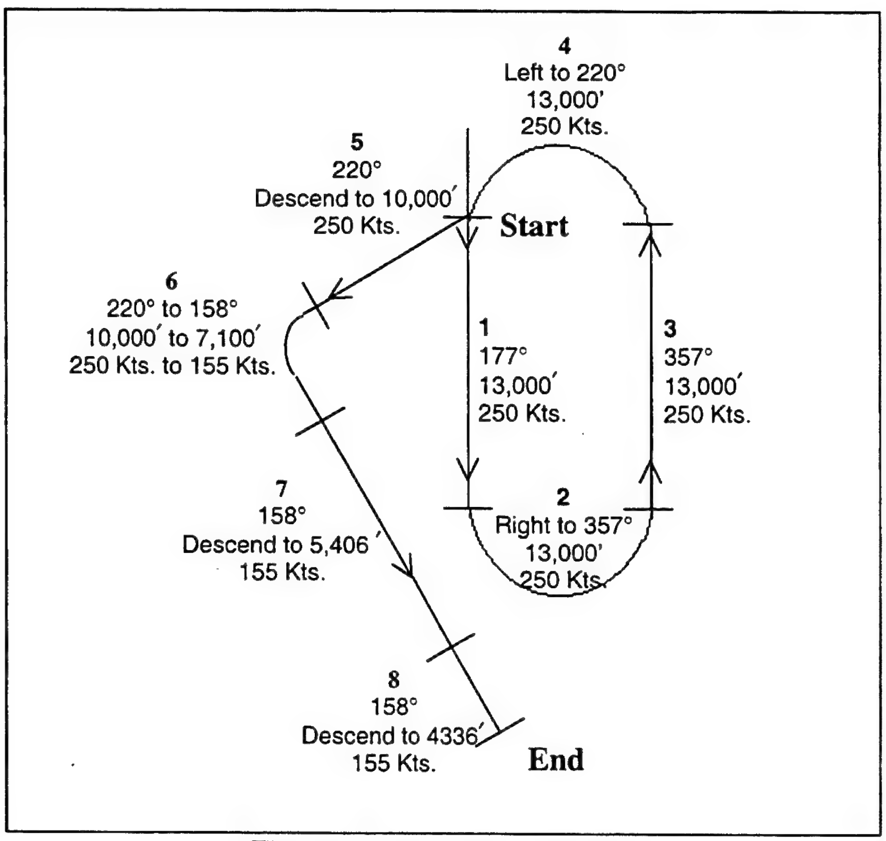
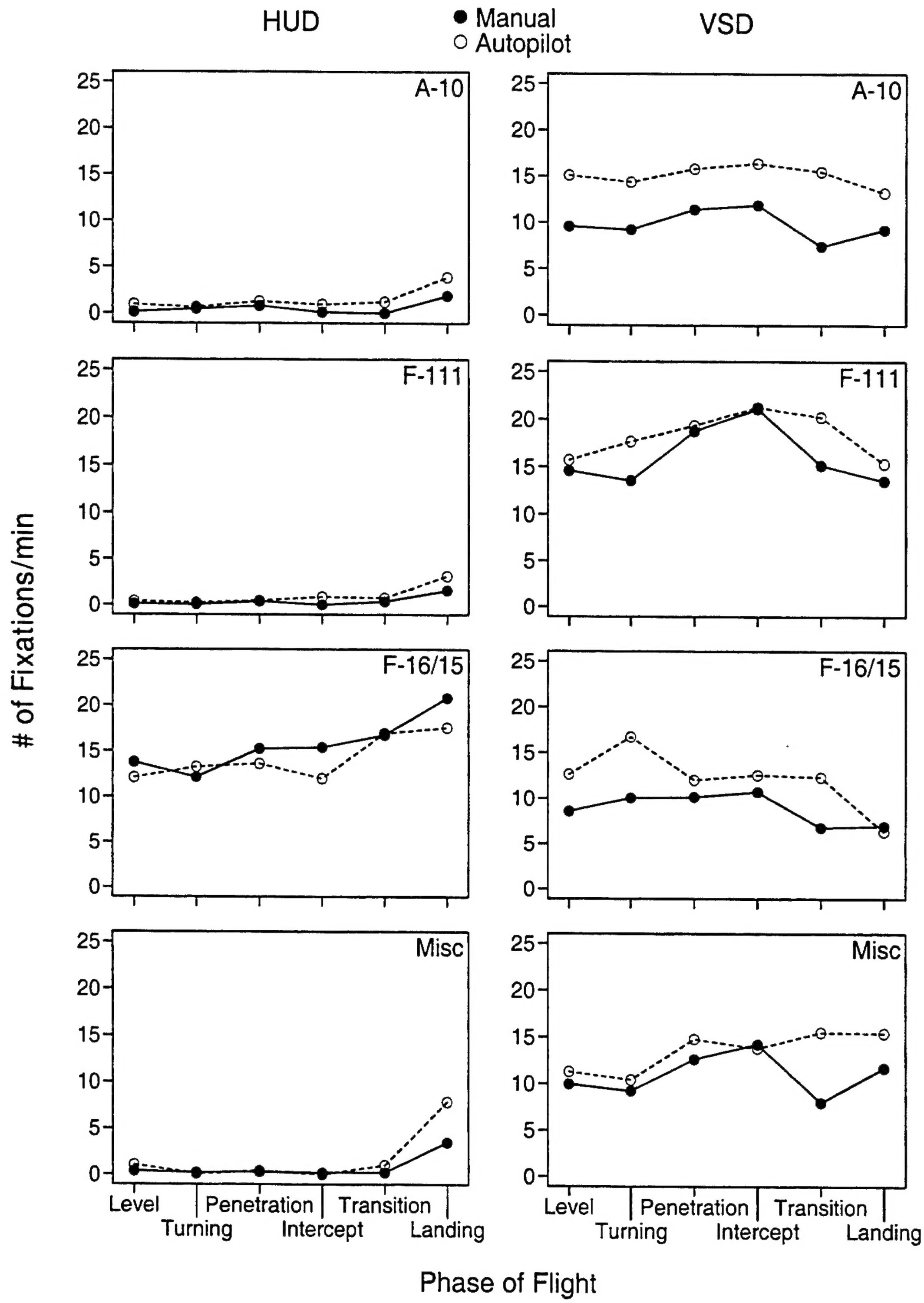


Figure 2. Instrument Approach

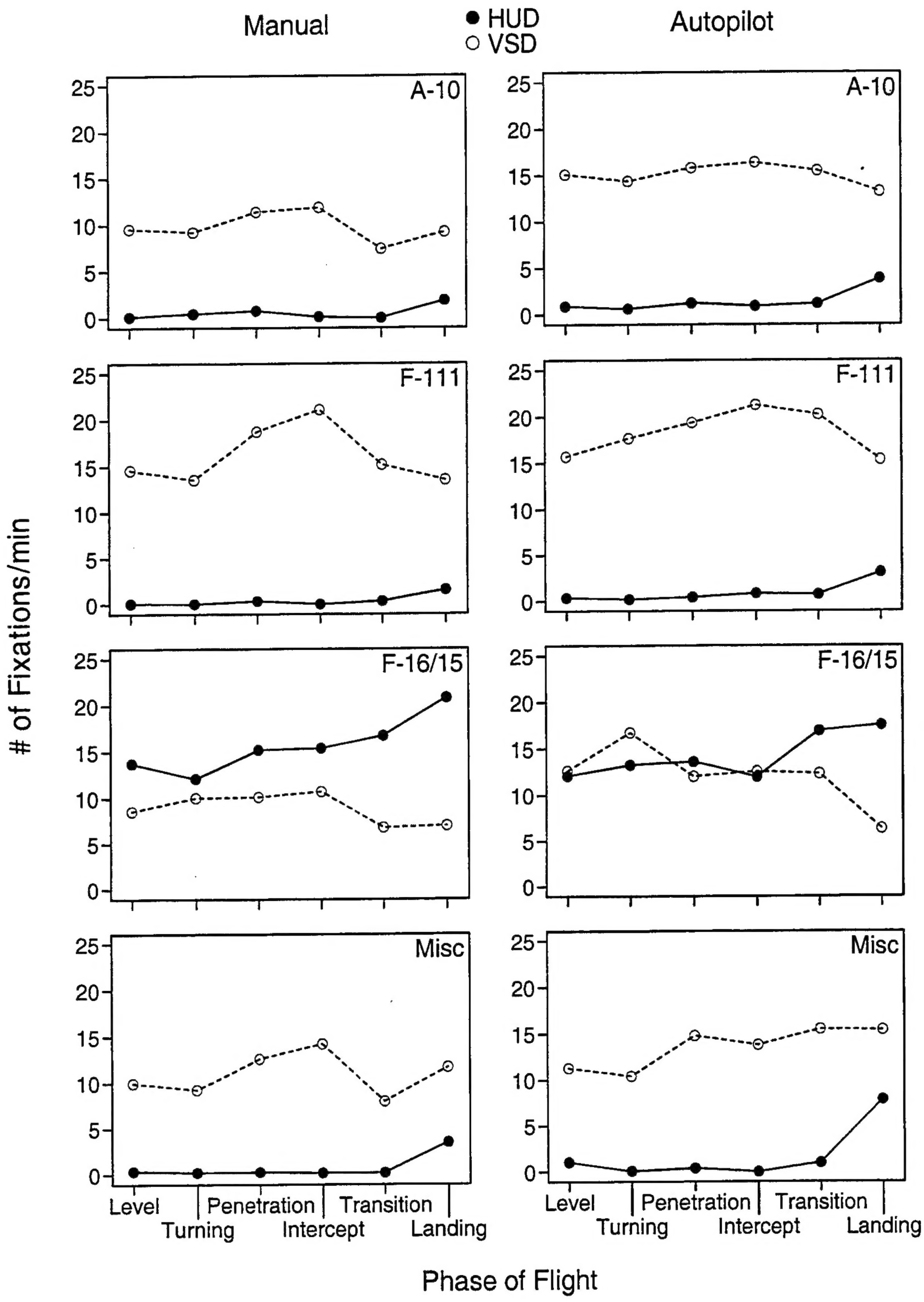
Group	Display	Manual			Autopilot		
		# of Fixations per min	**Dwell Time (sec)**	**Percent of Total Dwell Time**	**# of Fixations per min**	**Dwell Time (sec)**	**Percent of Total Dwell Time**
A-10 (N=5)	VSD	9.77	6.88	85.78	15.04	2.66	60.07
	DEP	0.42	0.55	0.31	2.69	0.60	2.95
	HSD	4.85	0.67	5.95	5.77	1.27	12.37
	HUD	0.54	0.66	0.68	1.45	0.58	1.63
	ALT	0.37	0.51	0.30	0.65	0.32	0.37
	ADI	0.27	0.60	0.33	0.69	0.41	0.53
	HSI	1.17	0.59	1.10	2.21	0.49	1.72
	ENG	0.26	0.55	0.28	0.52	0.47	0.43
	RADALT	0.59	0.67	0.63	0.89	0.65	0.94
	OTHER	5.54	0.49	4.64	16.88	0.69	18.99
F-111 (N=7)	VSD	16.12	3.37	79.54	18.27	1.67	48.68
	DEP	0.85	0.54	0.85	3.74	0.69	4.55
	HSD	3.55	0.51	3.47	6.22	0.94	9.74
	HUD	0.39	0.28	0.26	0.95	0.51	0.97
	ALT	1.84	0.33	1.17	1.78	0.39	1.38
	ADI	1.75	0.48	1.75	1.44	0.42	1.22
	HSI	4.79	0.47	3.83	6.12	0.66	7.08
	ENG	0.21	0.39	0.15	0.29	0.28	0.16
	RADALT	0.20	0.32	0.12	0.44	0.39	0.35
	OTHER	12.50	0.42	8.86	20.47	0.74	25.87
F-16/15 (N=4)	VSD	8.88	1.25	24.98	12.10	1.23	23.85
	DEP	1.09	0.33	0.54	4.78	0.59	5.38
	HSD	5.43	0.55	5.82	7.82	0.91	13.69
	HUD	15.67	2.01	57.16	14.22	0.93	23.78
	ALT	1.81	0.32	0.99	2.70	0.38	1.97
	ADI	0.92	0.32	0.63	0.74	0.47	0.60
	HSI	3.88	0.37	2.69	3.69	0.56	3.71
	ENG	0.12	0.39	0.09	0.65	0.32	0.37
	RADALT	0.13	0.32	0.07	1.10	0.42	0.91
	OTHER	8.45	0.56	7.03	23.95	0.68	25.74
Misc (N=5)	VSD	10.95	5.96	84.92	13.53	2.43	53.94
	DEP	0.65	0.44	0.54	4.34	0.86	6.53
	HSD	4.23	0.62	5.01	8.12	1.23	17.00
	HUD	0.78	1.79	1.91	1.72	0.93	3.20
	ALT	0.20	0.32	0.12	1.01	0.43	1.27
	ADI	0.43	0.49	0.29	0.60	0.39	0.46
	HSI	1.00	0.47	0.90	1.82	0.55	1.64
	ENG	0.62	0.47	0.44	0.54	0.50	0.44
	RADALT	0.45	0.41	0.32	0.80	0.45	1.24
	OTHER	6.16	0.70	5.56	13.75	0.62	14.28

Table I



HUD
● Manual
○ Autopilot
VSD
A-10
F-111
F-16/15
Misc
# of Fixations/min
0
5
10
15
20
25
Level
Turning
Penetration
Intercept
Transition
Landing
Phase of Flight

Figure 3.



Manual
● HUD
○ VSD
Autopilot
A-10
F-111
F-16/15
Misc
25
20
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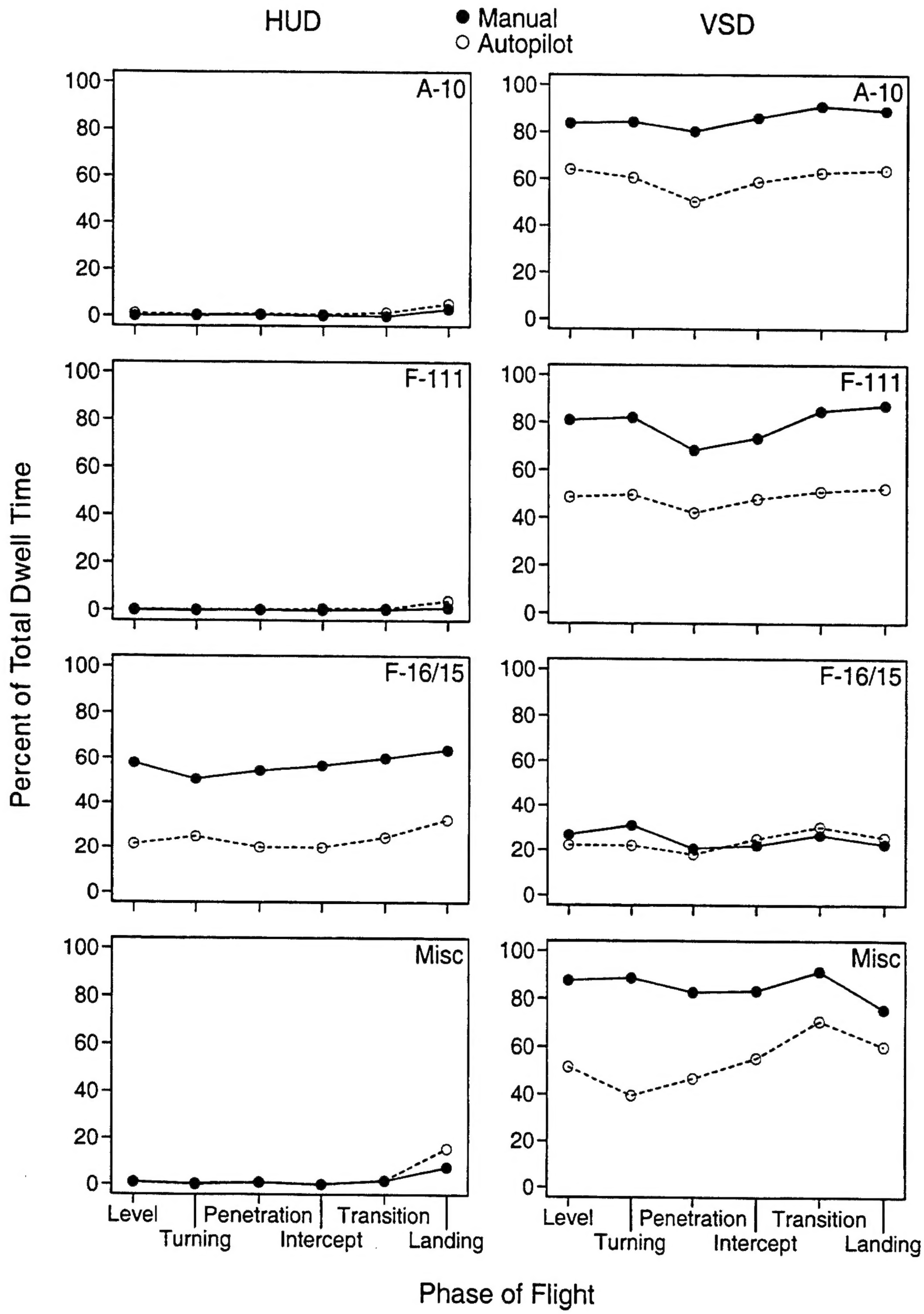
0
# of Fixations/min
Level
Turning
Penetration
Intercept
Transition
Landing
Phase of Flight

Figure 4.



HUD
● Manual
○ Autopilot
VSD
A-10
F-111
F-16/15
Misc
100
80
60
40
20
0
Percent of Total Dwell Time
Level
Turning
Penetration
Intercept
Transition
Landing
Phase of Flight

Figure 5.